# Computational biomechanics : from animal locomotion to the cardiovascular system (Fast Algorithms in Computational Fluids : theory and applications)

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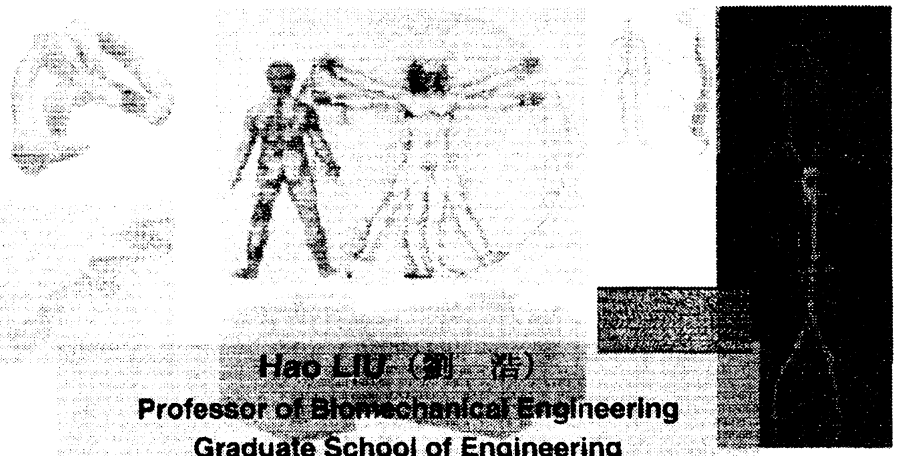
# Computational biomechanics:
## from animal locomotion to the cardiovascular system



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Graduate School of Engineering
Chiba University, JAPAN

2008.2.18-20 Kyoto Workshop on Computational Fluids

# Why Computational Biomechanics
## Physiom of Circulatory system

**Biological systems and hence biomechanics are, in general, "complex systems", which need to be modeled as realistically as possible so that we can avoid some pitfalls.**

An 'alive' CVS modeling for the whole body

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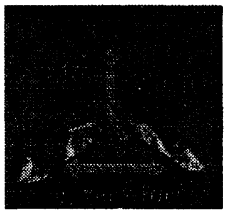
## FOUR Dynamic Phenomena in Insect Flight

Force generation mechanisms



Flight control mechanisms

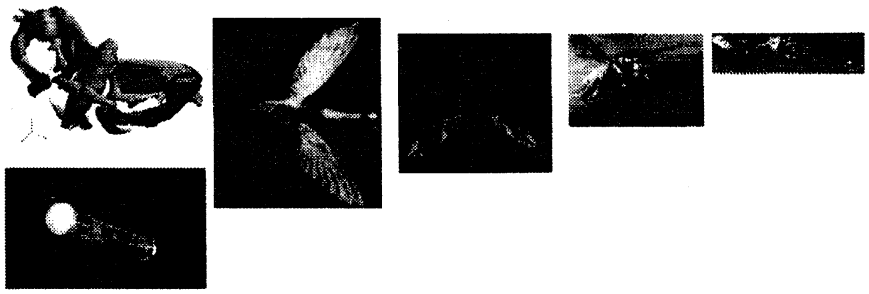
@Complicated wing kinematics
@Unsteady aerodynamics in terms of vortex dynamics
@Low Res<$10^4$
@Conventional 'quasi-steady' theory never works

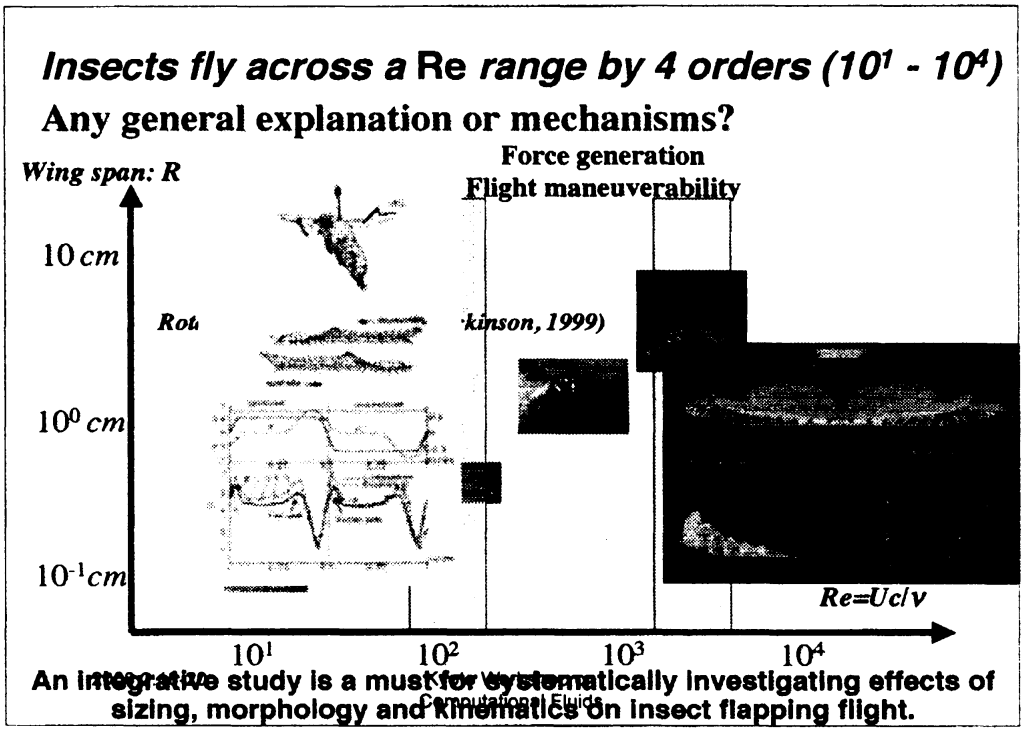
@Multi-body Dynamics with 6DOF
@High freq. 20~1000Hz
@Dynamic flight stability
@Maneuverability

**Four Dynamics, large-scale simulation on flight dynamics, aerodynamics, structural dynamics, and thermodynamics**



## Novel Mechanisms in Insect Flapping Flight




Insects fly across a Re range by 4 orders ($10^1$ - $10^4$)
Any general explanation or mechanisms?
Wing span: R
Force generation
Flight maneuverability
10 cm
$10^0$ cm
$10^{-1}$cm
Re=Uc/ν
$10^1$
$10^2$
$10^3$
$10^4$
An integrative study is a must for systematically investigating effects of sizing, morphology and kinematics on insect flapping flight.
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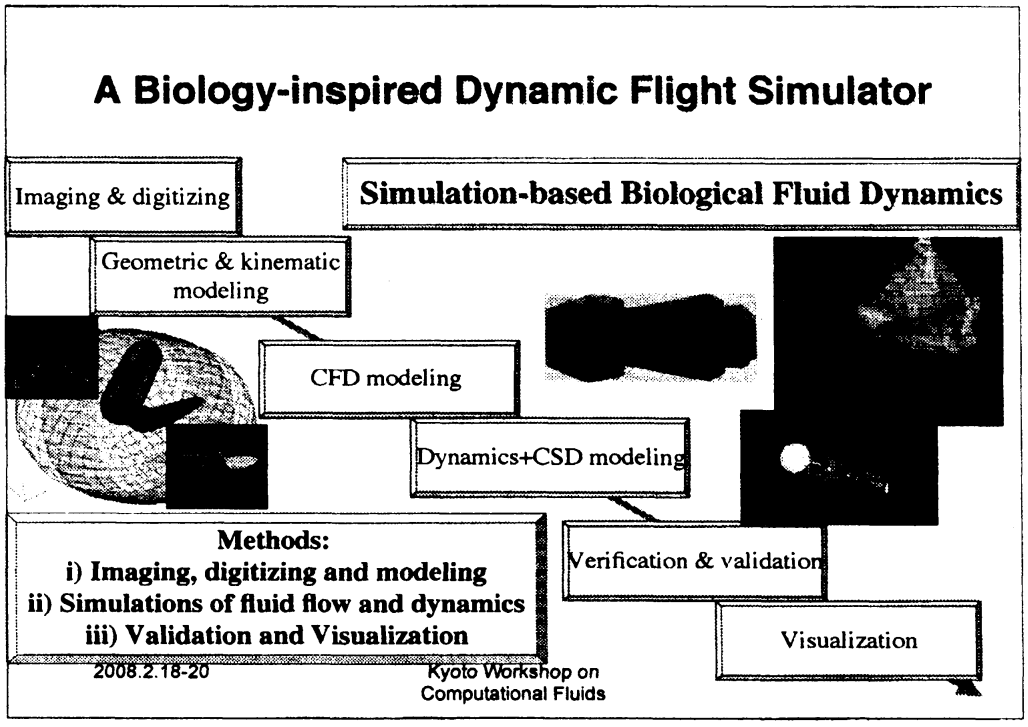
A Biology-inspired Dynamic Flight Simulator
Imaging & digitizing
Simulation-based Biological Fluid Dynamics
Geometric & kinematic modeling
CFD modeling
Dynamics+CSD modeling
Verification & validation
Visualization
Methods:
i) Imaging, digitizing and modeling
ii) Simulations of fluid flow and dynamics
iii) Validation and Visualization
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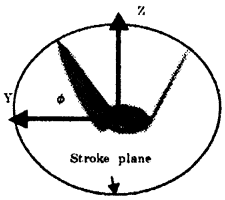
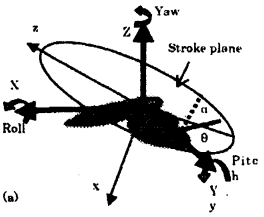
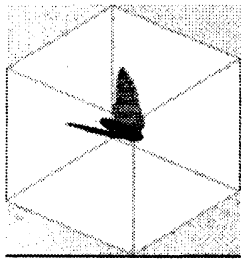
## *A Biology-inspired Dynamic Flight Simulator* continued

Aerodynamics

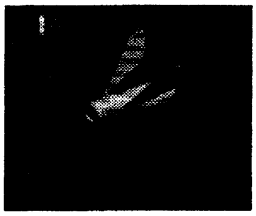
Energetics: Force, Moment and Power



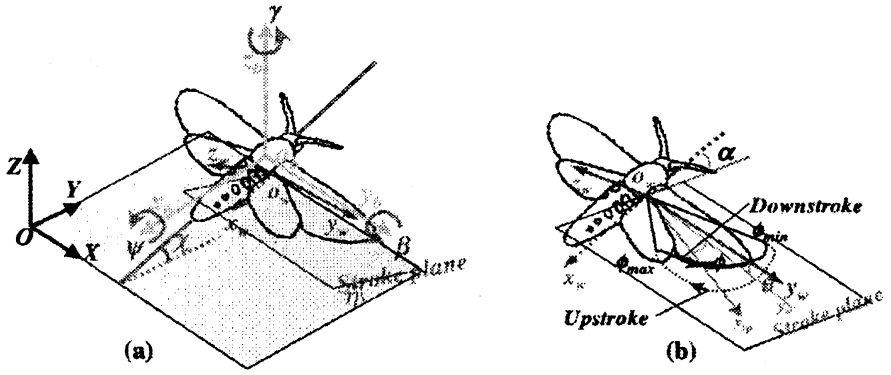



Flight dynamics



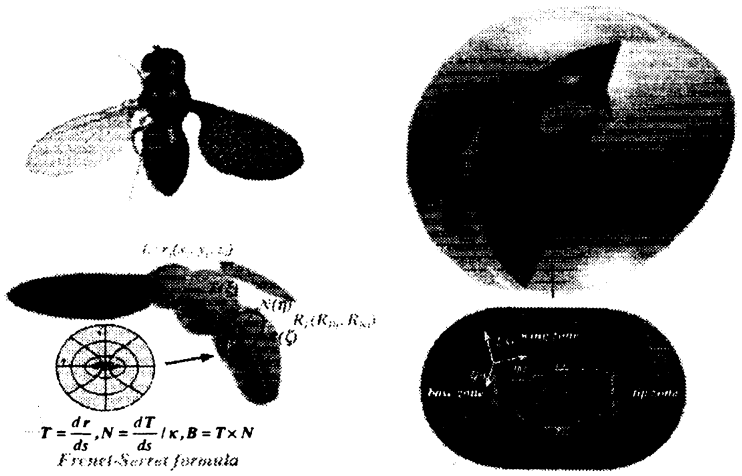
Pressure-gradient, Centrifugal, and Coriolis forces






(a) Three systems: wing-fixed system ($x_w$, $y_w$, $z_w$), the body-fixed system ($x_b$, $y_b$, $z_b$), and the global system ($X$, $Y$, Z); the stroke plane angle $\eta$ and the body angle $\chi$; the angles of pitch $\beta$, roll $\psi$, and yaw $\gamma$ with respect to the body-fixed system.

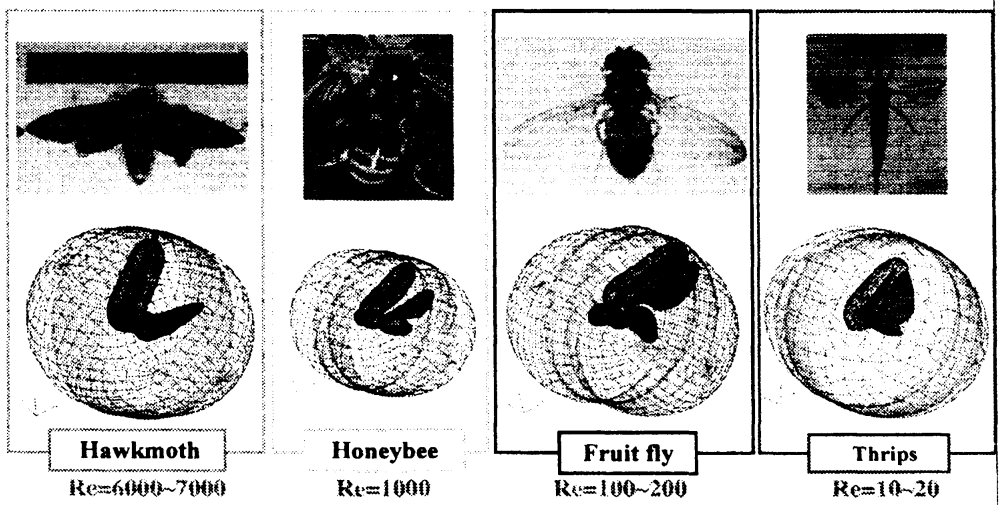
(b) Wing position parameters within the stroke plane: the wingtip path, the positional angle $\phi$, the elevation angle $\theta$, and the angle of attack $\alpha$.




(a) A top-view fruit fly with a computer model superimposed on the right half and a perspective view of the model with the extracted body centerline $L$ and elliptic cross sections.
(b) A three-block model and grid systems for the fruit fly with two wing-fitted blocks immersed within a body-fitted block.



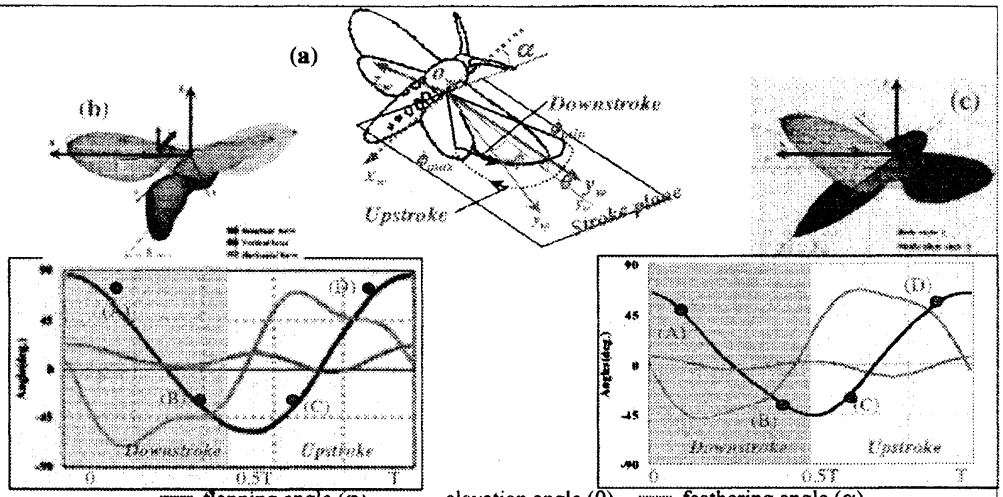
## Morphological models of four typical insects over a wide range of *Res* of $O(10^1)$ to $O(10^4)$




**Hawkmoth: wing(45×45×31),body(45×43×95) Honeybee: wing(45×45×31), body(45×45×95)**
**Fruit fly: wing(45×45×31), body(45×47×95) Thrips: wing(45×45×45), body(51×51×95)**



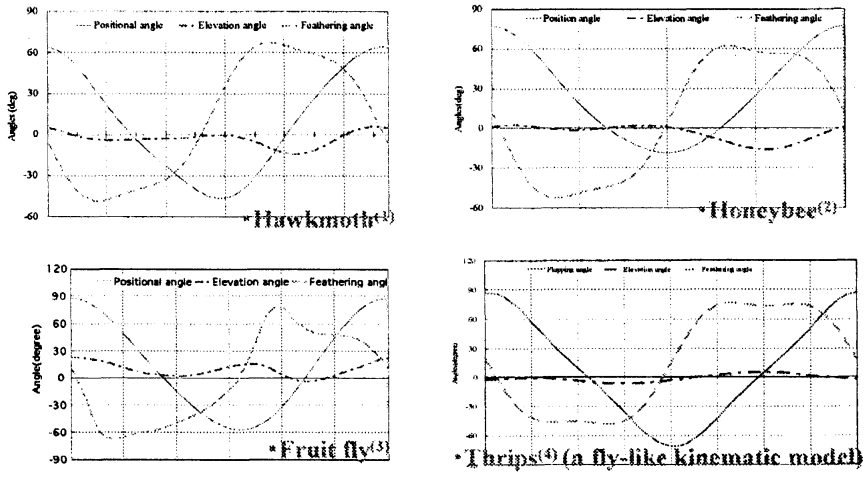
Outer-boundary : $20R_m$



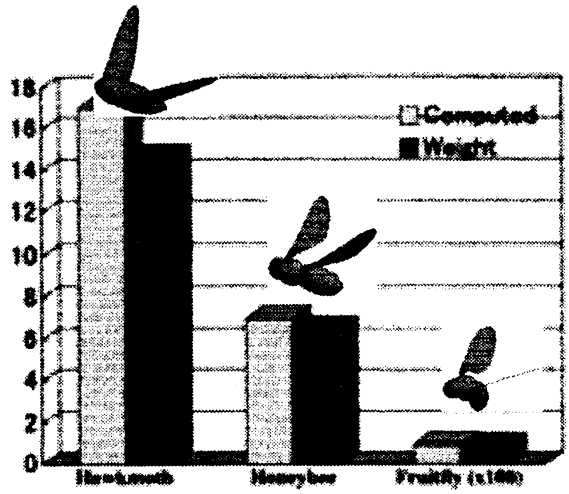

A fruit fly **(b)** flaps at a higher body angle ($\chi$=45.0 deg) but horizontally ($\beta$=0.0 deg) in an "eight-figure" motion; a hawk moth **(c)** hovers at a body angle ($\chi$=39.8 deg) and a stroke plane angle of ($\beta$ =15.0 deg), resulting in a curved elliptical wing tip path.



## Kinematic models of four typical insects

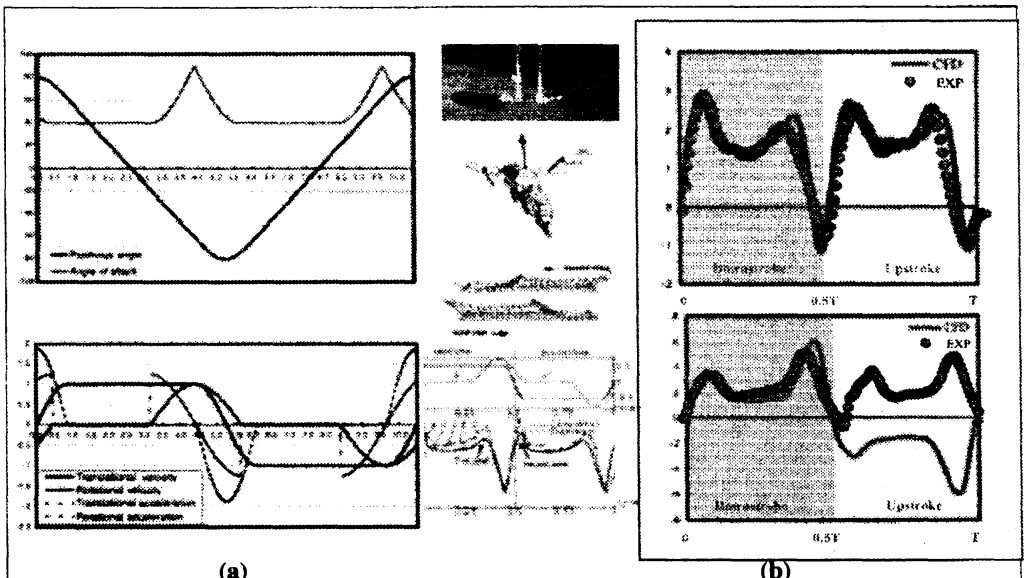



(1) A.P. Willmott., et al, *JEB*; 200 2705-2722 (1997)
(2) D.L. Altshuler., et al, *PNAS*; vol.102; no.50; 18213-18218 (2005)
(3) N.S. Fry, et al,, *JEB*; 208, 2303-2318 (2005)
(4) F.O. Lehmann, et al, *JEB*; 208, 3075-3092, (2005)



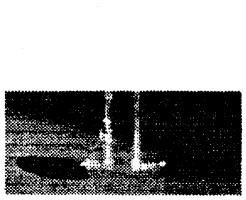

**Weights and computed lift forces ($mN$) in hovering flights of hawkmoth, honeybee and fruitfly.**



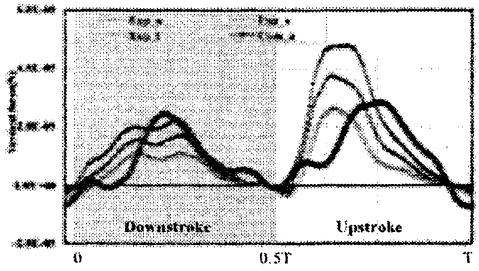



**(a)** **(b)**

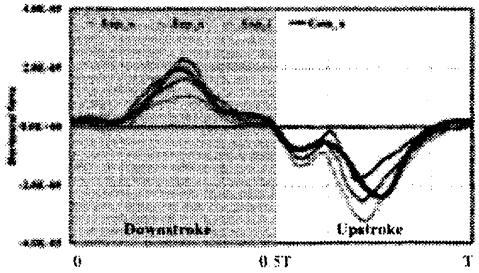
**(a) Idealized wing movements of translation and rotation (angles, velocities and accelerations). (b) Time course of lift and drag force coefficients compared with EXPs**



(a)



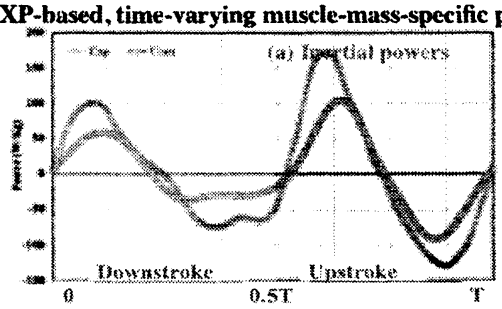

(b)

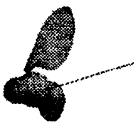




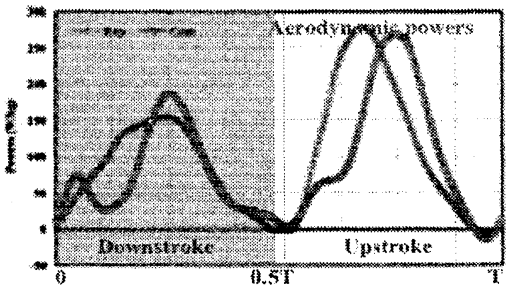

**Comparison of CFD and EXP-based, time-varying muscle-mass-specific powers**

(a)

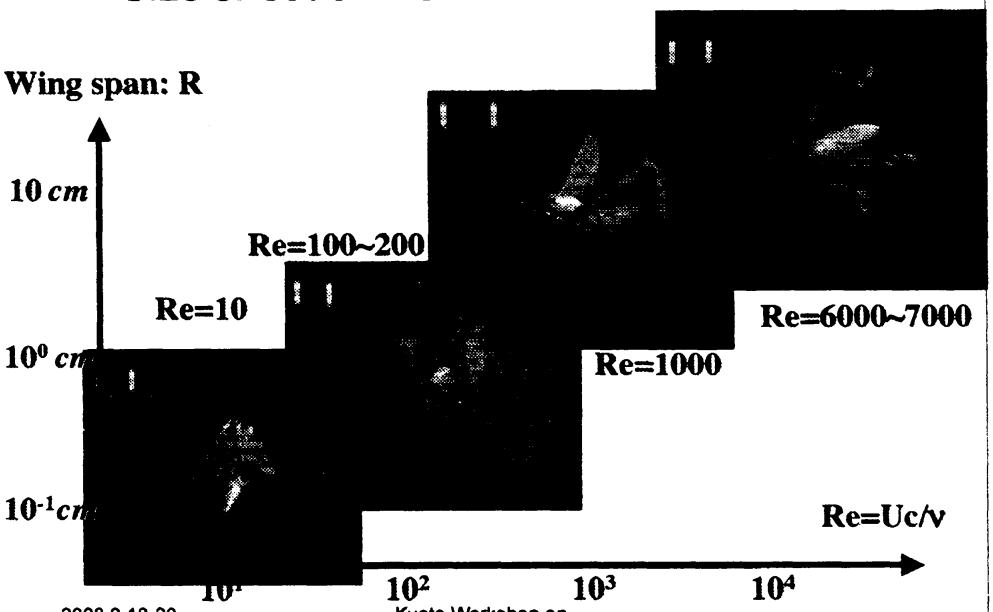


(b)



## Size effect on Near-and far field Flows

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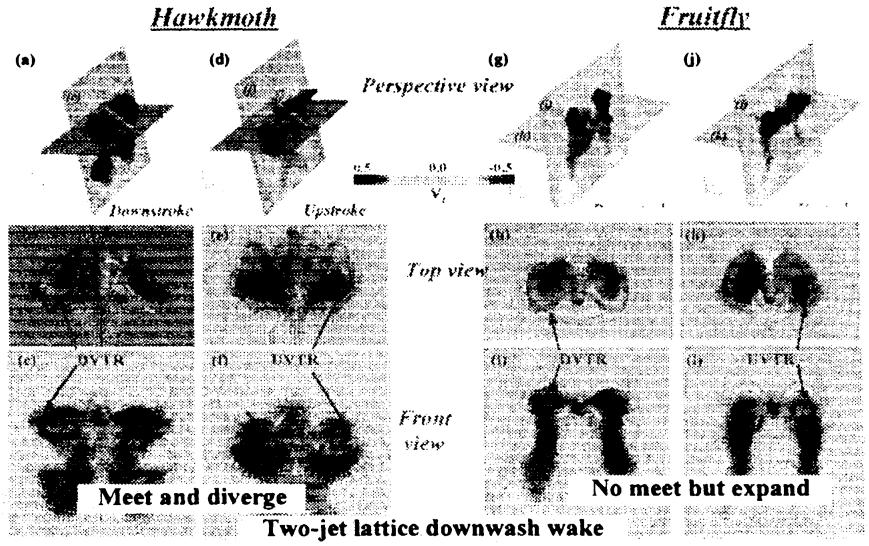


**Two-jet lattice downwash wake**

**Iso-velocity surfaces of $v_z$ = -0.5 in perspective views of (a), (d) and (g), (j); and by velocity contours and vectors in top and front views of (b), (c), (e), (f), and (h), (i), (k), (l), for hawkmoth and fruitfly hovering, respectively. The iso-vorticity surfaces are also visualized to illustrate the relationship between the downwashes and the VTRs.**

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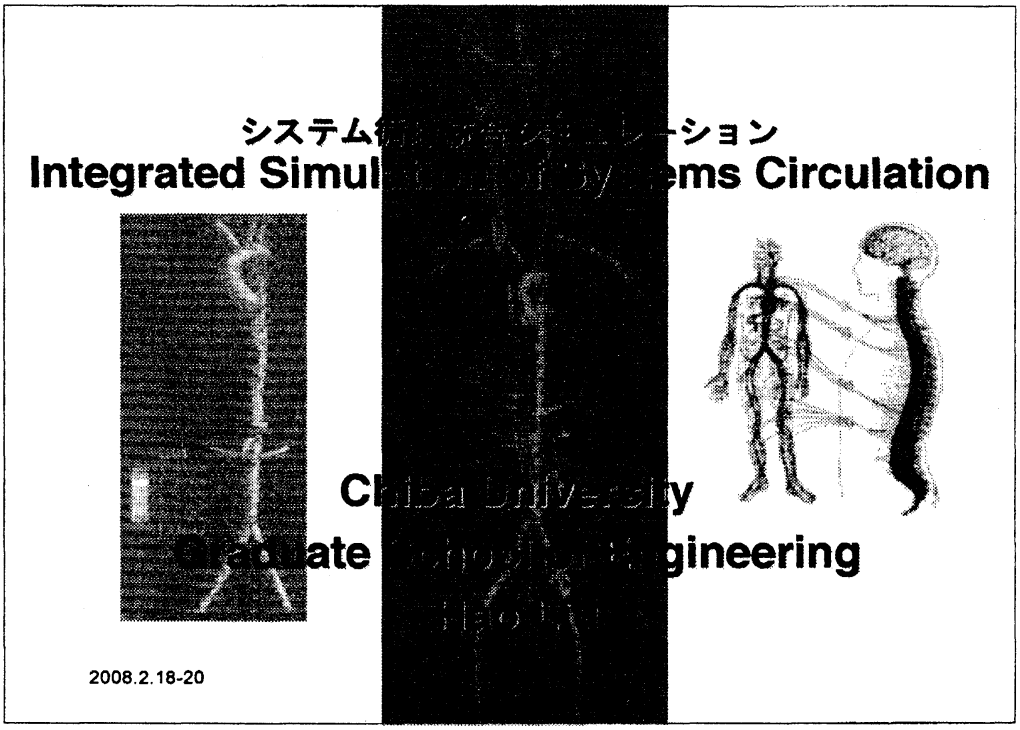
システム循環シミュレーション
Integrated Simul ems Circulation
Graduate
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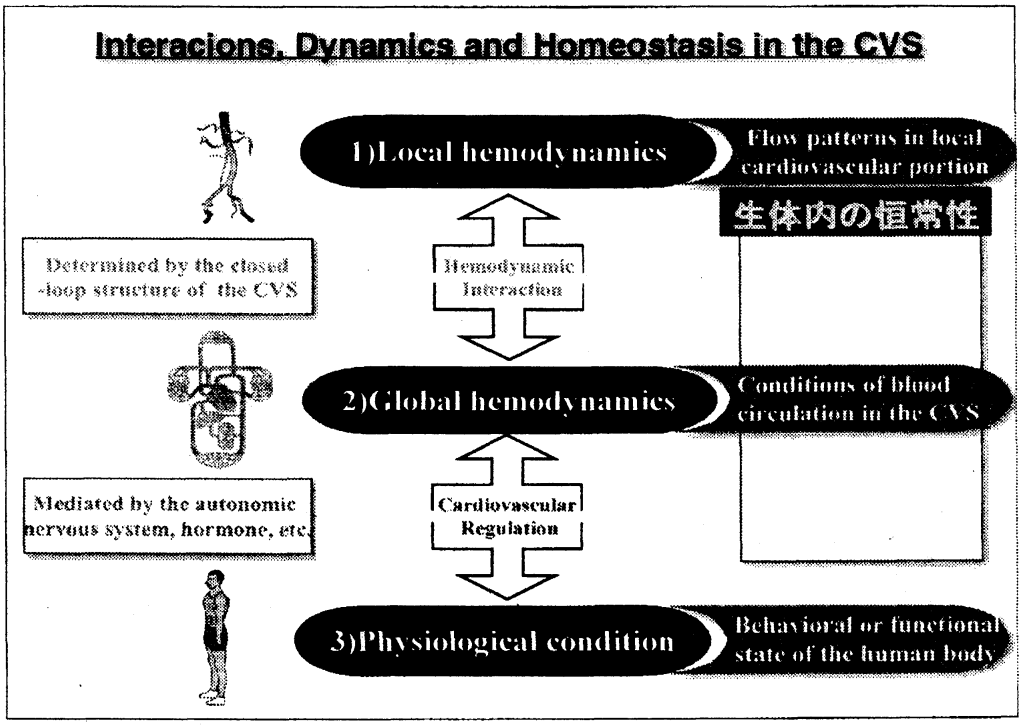
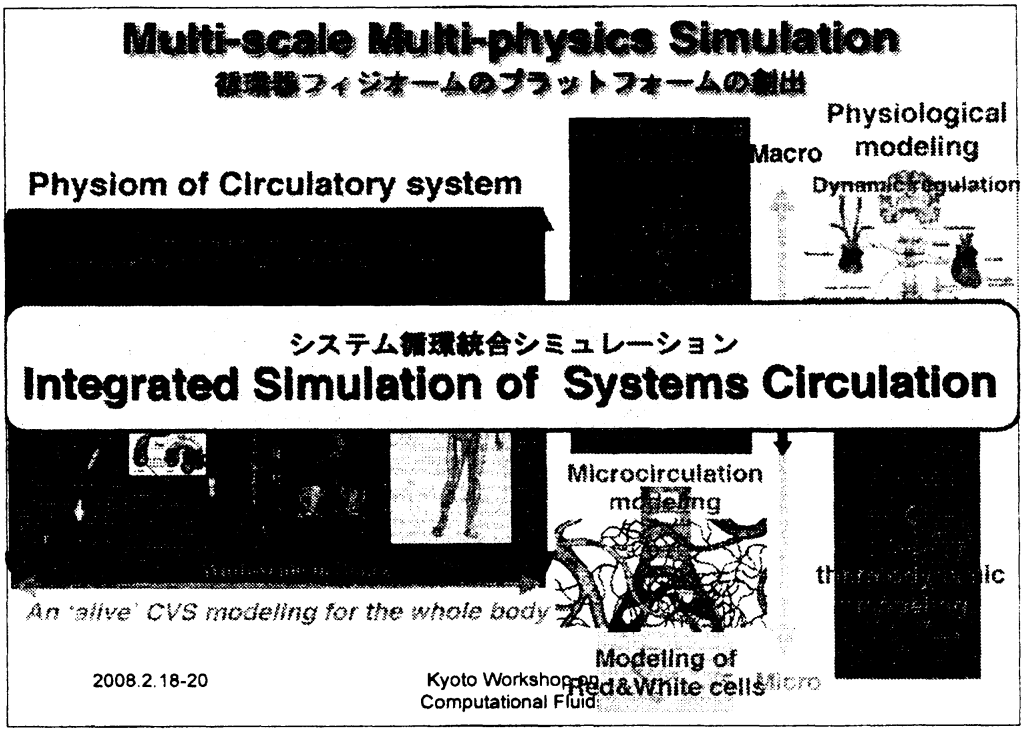

Interacions, Dynamics and Homeostasis in the CVS
1)Local hemodynamics
Flow patterns in local cardiovascular portion
生体内の恒常性
Determined by the closed -loop structure of the CVS
Hemodynamic Interaction
2)Global hemodynamics
Conditions of blood circulation in the CVS
Mediated by the autonomic nervous system, hormone, etc.
Cardiovascular Regulation
3)Physiological condition
Behavioral or functional state of the human body


Multi-scale Multi-physics Simulation
循環器フィジオームのプラットフォームの創出
Physiological modeling
Macro
Physiom of Circulatory system
Dynamic regulation
システム循環統合シミュレーション
Integrated Simulation of Systems Circulation
Microcirculation modeling
An 'alive' CVS modeling for the whole body
Modeling of Red&White cells
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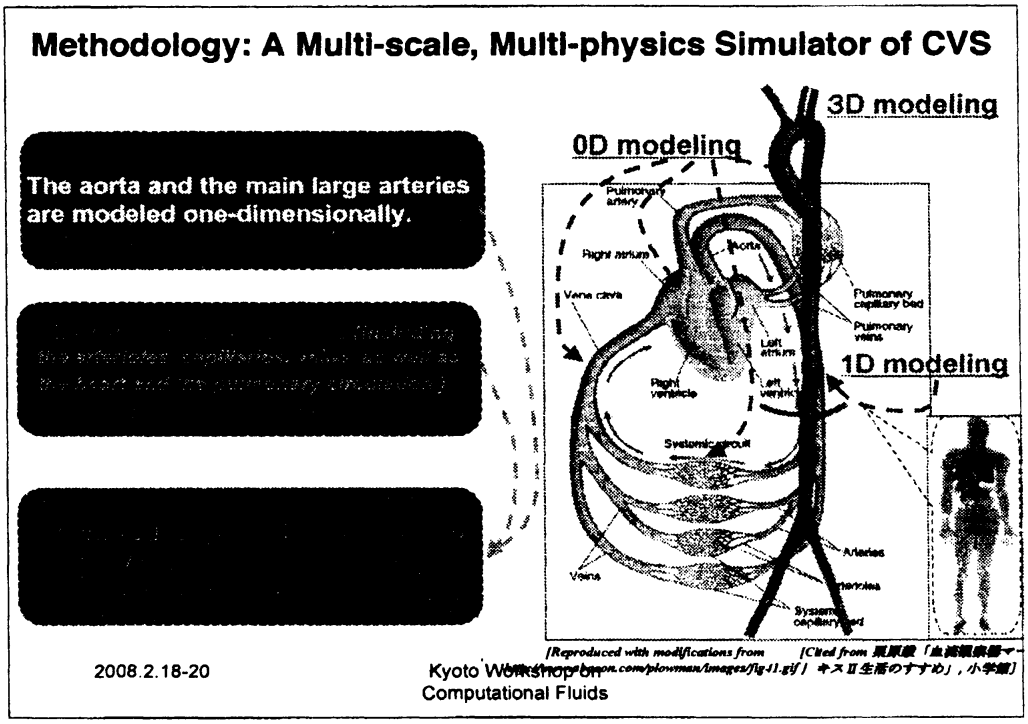
Methodology: A Multi-scale, Multi-physics Simulator of CVS
3D modeling
0D modeling
The aorta and the main large arteries are modeled one-dimensionally.
1D modeling
Pulmonary artery
Right atrium
Aorta
Vena cava
Pulmonary capillary bed
Pulmonary veins
Left atrium
Right ventricle
Left ventricle
Systemic circuit
Arteries
Veins
Systemic capillary bed
[Reproduced with modifications from
[Cited from 坂原俊「血液循環器マー
キスII生活のすすめ」, 小学館]
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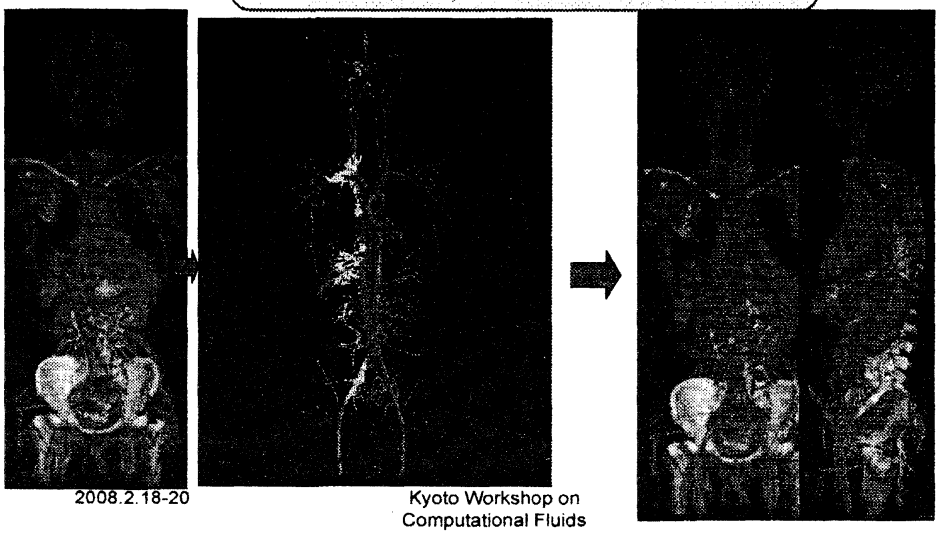
Computational Fluids

## A prototype, anatomically realistic arterial-and venous -tree model

**A Global Arterial- and Venous-Tree model**
A VHP-based prototype model (A:266; V:117)
A CT/MRI-based, individual model



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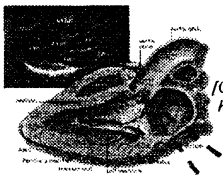
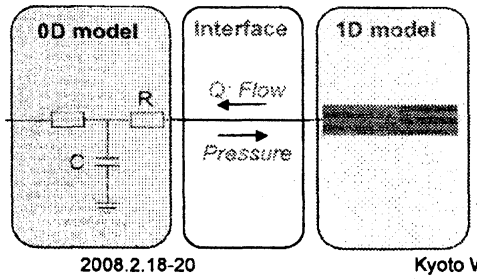
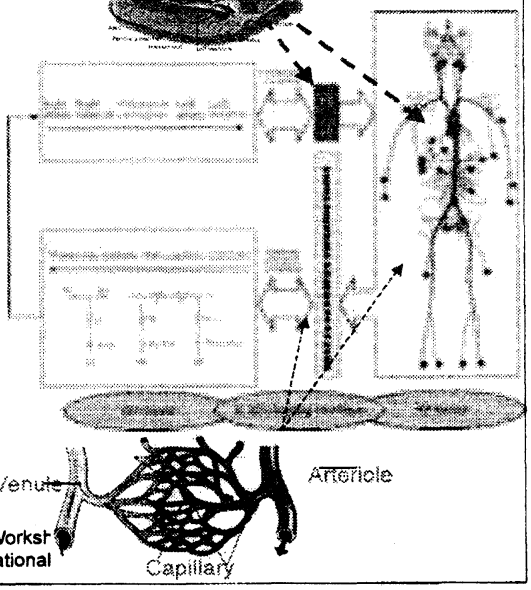
## 0-1D coupling methods



*[Cited with modifications from http://www.med.yale.edu ]*

0-1D coupling is implemented at the aortic inlet and the distal ends of the large arteries via pressure-flow exchange.

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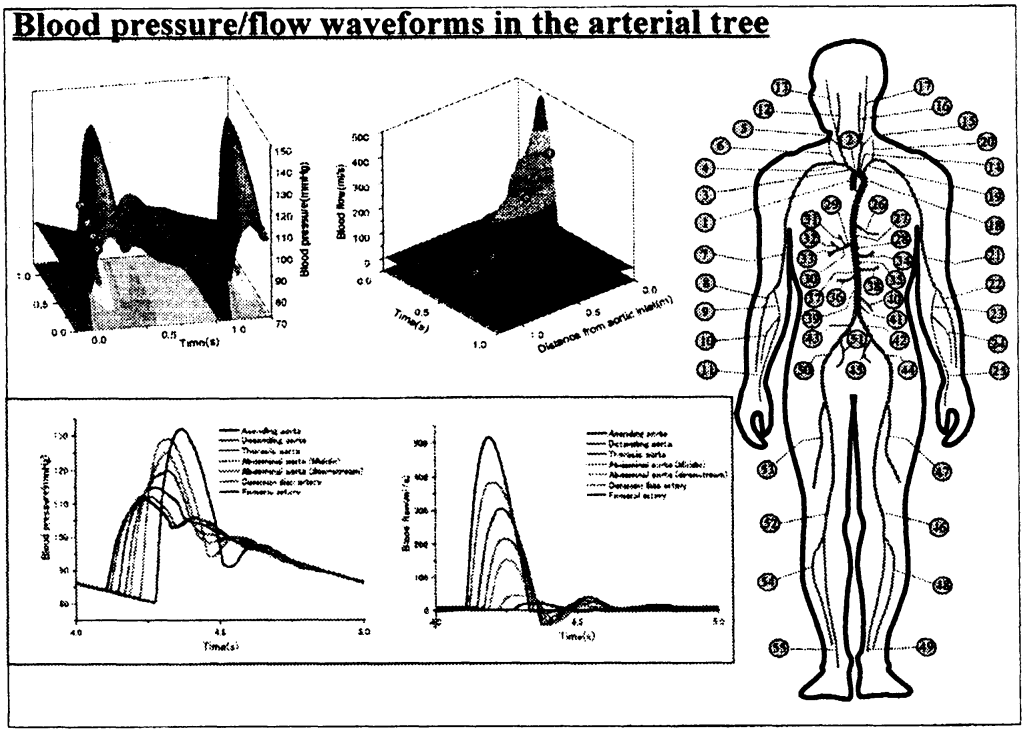
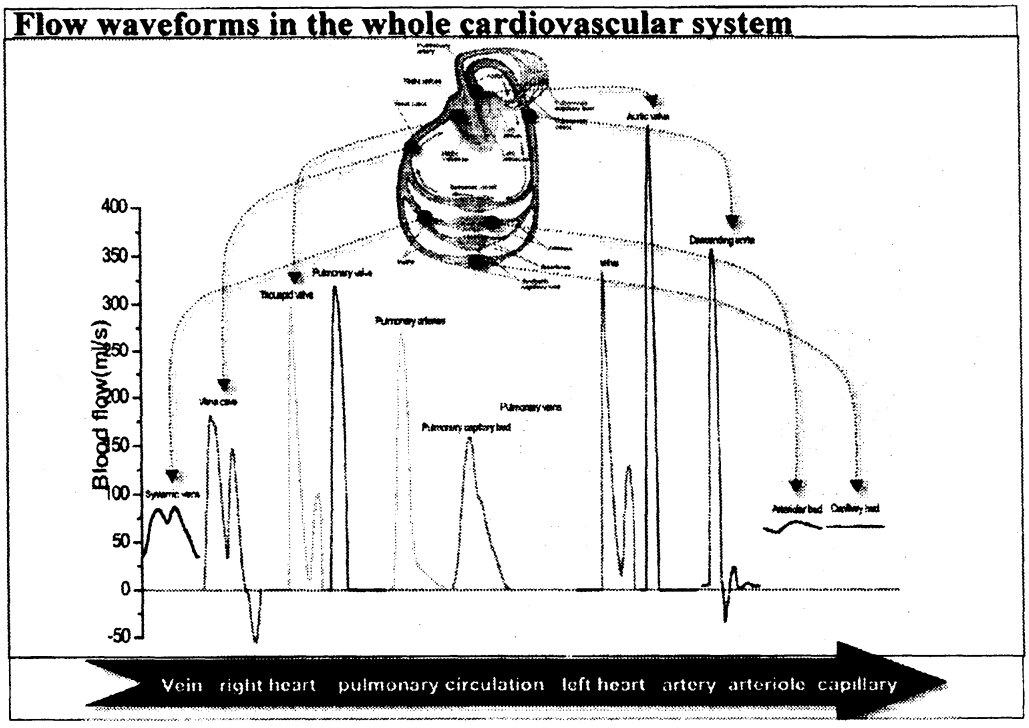
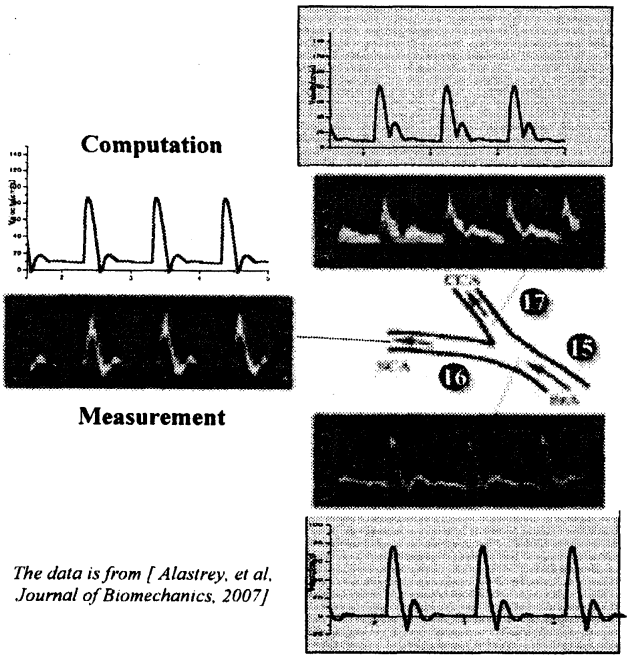
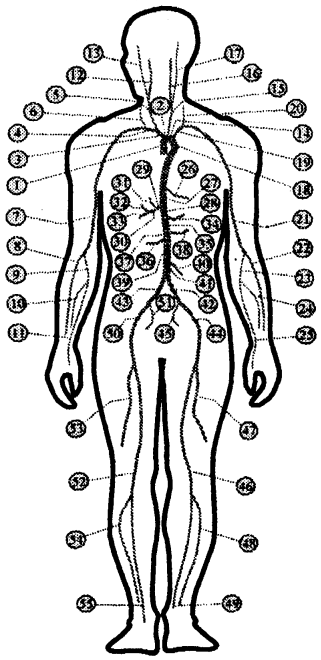

Blood pressure/flow waveforms in the arterial tree


Flow waveforms in the whole cardiovascular system
Blood flow(ml/s)
Vein right heart pulmonary circulation left heart artery arteriole capillary

## Comparison with physiological data

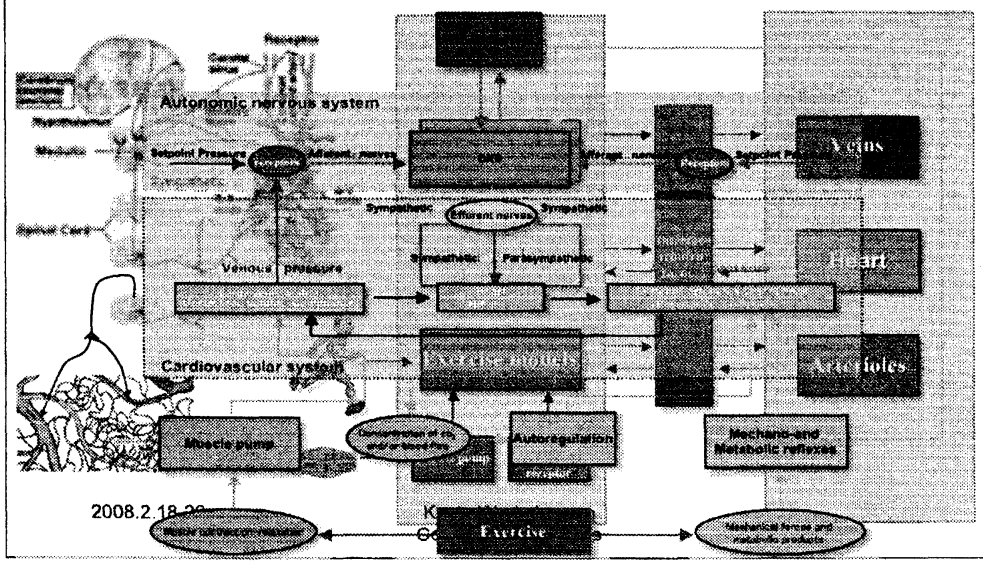


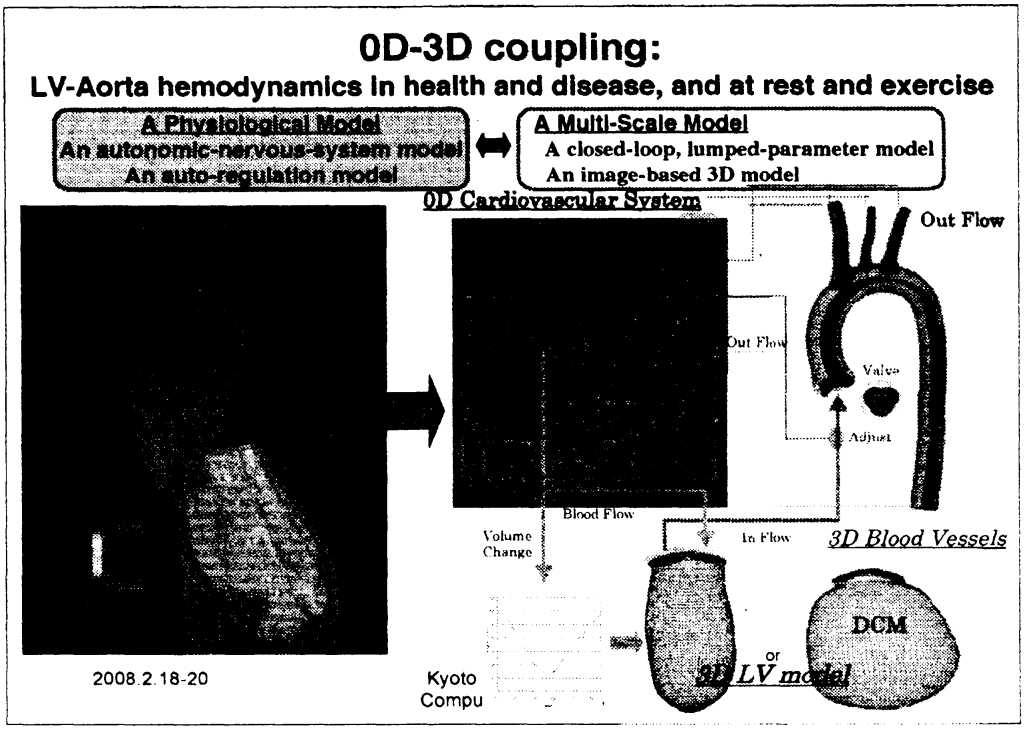

*The data is from [ Alastrey, et al, Journal of Biomechanics, 2007]*



## ANS Modeling

### Physiological models and their coupling with 0D model




0D-3D coupling:
LV-Aorta hemodynamics in health and disease, and at rest and exercise
A Physiological Model
An autonomic-nervous-system model
An auto-regulation model
A Multi-Scale Model
A closed-loop, lumped-parameter model
An image-based 3D model
0D Cardiovascular System
Out Flow
Out Flow
Valve
Adjust
Blood Flow
Volume Change
In Flow
3D Blood Vessels
DCM
or
3D LV model
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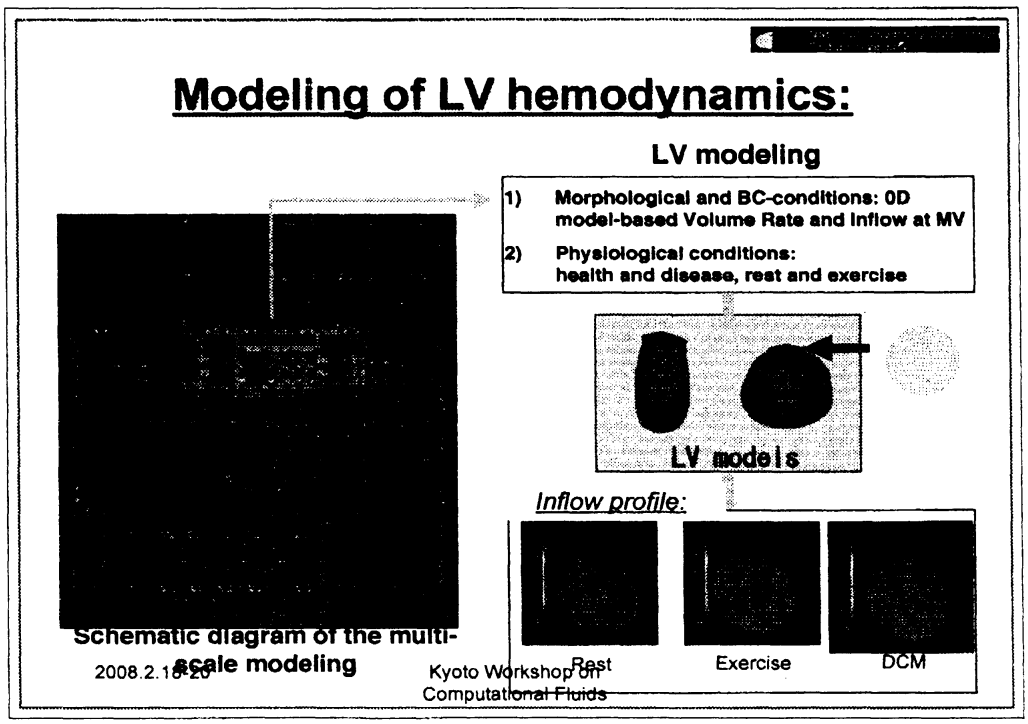
Compu


Modeling of LV hemodynamics:
LV modeling
1) Morphological and BC-conditions: 0D model-based Volume Rate and Inflow at MV
2) Physiological conditions: health and disease, rest and exercise
LV models
Inflow profile:
Rest
Exercise
DCM
Schematic diagram of the multi-scale modeling
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## LV hemodynamics: DCM

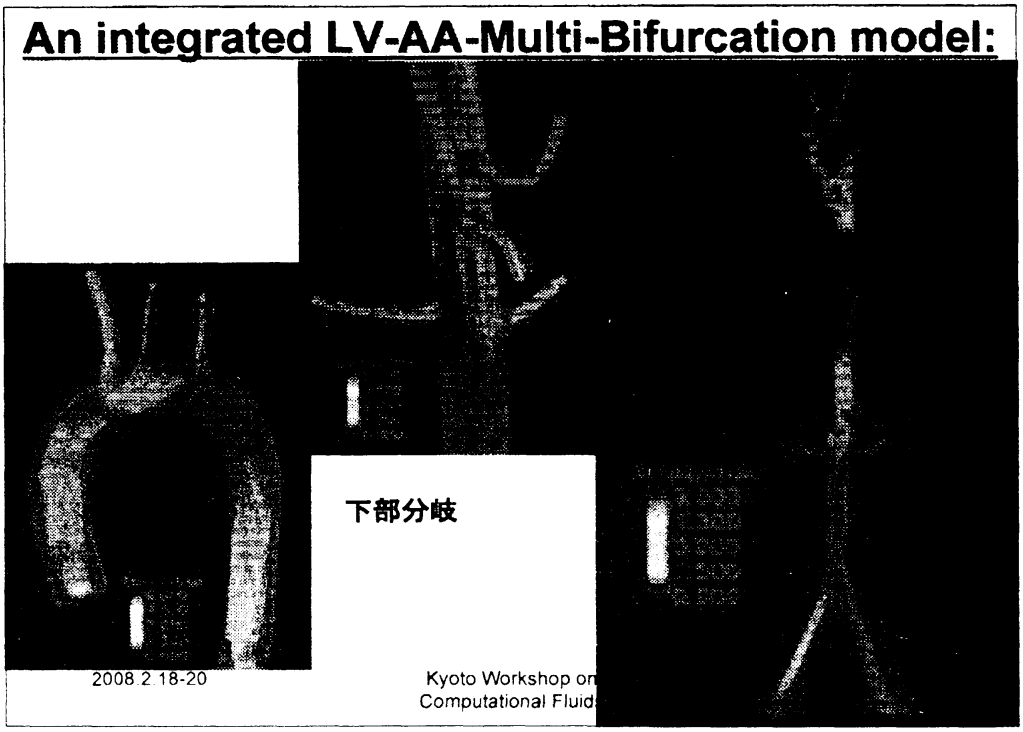
The vortex ring in the vicinity of ventricle apex persists almost a whole cardiac cycle, especially the presence of the vortex ring in systole is thought to dissipate the contraction energy of ventricle thus compromising the ventricular pumping function.

Summary:
Enlargement of the ventricle
Spherical transformation of the ventricular shape



## An integrated LV-AA-model:

**Rest** **Exercise** **DCM**


An integrated LV-AA-Multi-Bifurcation model:
下部分岐
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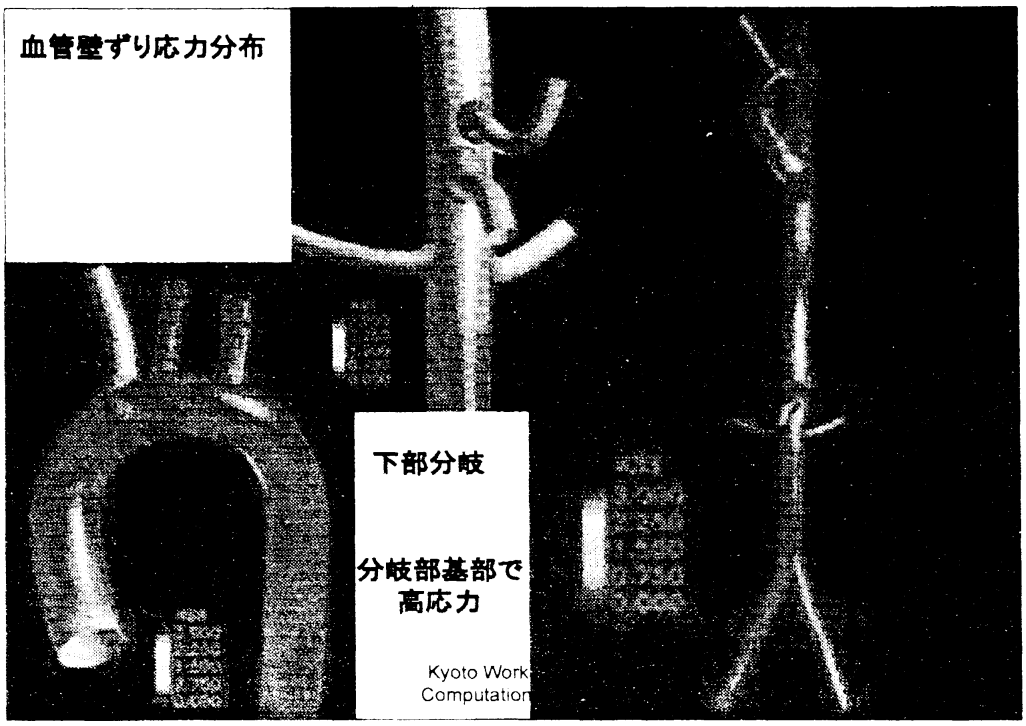
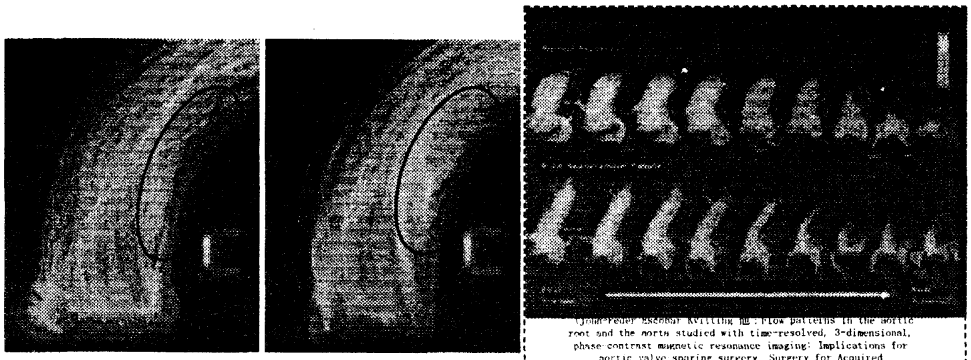

血管壁ずり応力分布
下部分岐
分岐部基部で
高応力
Kyoto Work
Computation

# Influence of valsalva sinus

MRA measurement



With sinus Without sinus

[John Fedor Bassem Kvitting M... Flow patterns in the aortic root and the aorta studied with time-resolved, 3-dimensional, phase contrast magnetic resonance imaging: Implications for aortic valve sparing surgery. Surgery for Acquired Cardiovascular Disease, 2009;5:91]

**The valsalva sinus seems to stabilize the vortex flow in the Asc. A.**



# Influence of valsalva sinus

**Measured** **Computed**

# Future Directions

- **Physically, it should be integrated.**
  **Multi-scale and multi-physics over a huge range on an order of $10^9$**
- **Computationally, it must be large-scale.**
  **Parallelization and grid computing**
- **In interdisciplinary, it should merge with experiments.**
  **Systematic verification & validation,**
  ***in vivo* and *in vitro***



A universal rule in biological systems:

# Local Worse, Global Best!

# Toward 'Computational' System Biomechanics